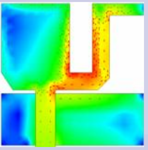
International Workshop on Antenna Technology



Metamaterial Antennas:
From Physics To Designs

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Founding General Chairs, iWAT, IS 3T-in-3A, APCAP, IMWF

Current research interest: **applied electromagnetic, metamaterials, and antennas for microwave, mmW, submmW, and THz systems**.

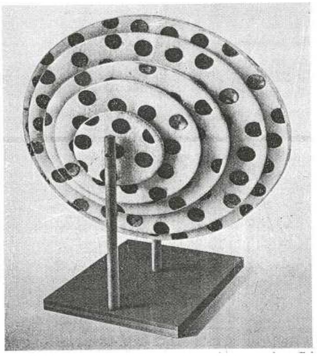
140 keynotes & invited talks, **400** papers, **4** books, **31** patents, **28** licenses

In this talk,

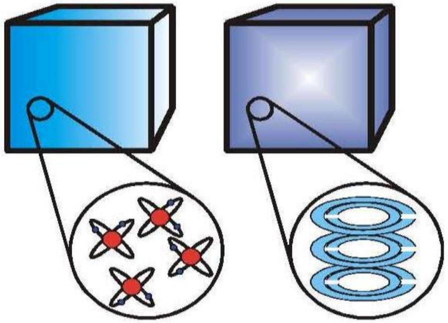
- **Background**
  - **Brief History Review**
  - **Potentials & Challenges in Antenna Engineering**
  - **State-of-the-art Designs**
- **Rethinking**
  - **Strategy**
  - **Metamaterial-based Antennas**
  - **Case study**
- **Comments**

Background Information:

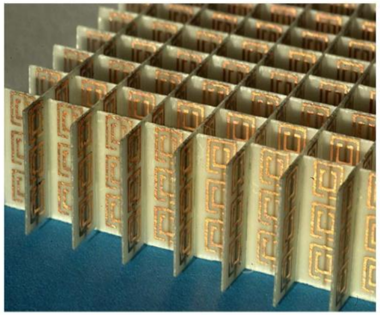
Brief Historic Review



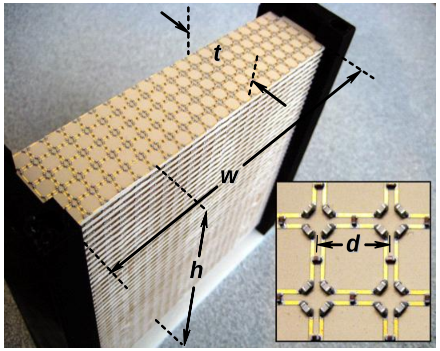
Artificial dielectric
by Kock in1948[1]



Artificial Molecules in
NIM by Pendry in 2000[2]



Experimental NIM
by Smith in 2001



Transmission-line based NIM
by Eleftheriades in 2002

1. The term artificial dielectric was originated by Winston E. Kock in 1948 when he was employed by Bell Laboratories.
2.J. B. Pendry, “Metamaterials and the Control of Electromagnetic Fields”

Background Information: **Brief Historic Review**

Pioneering Work: *Negative Index*

In 2000, Sir Pendry published a short but explosive paper in PRL explaining the theoretical possibility of a perfect lens.

Negative Refraction Makes a Perfect Lens

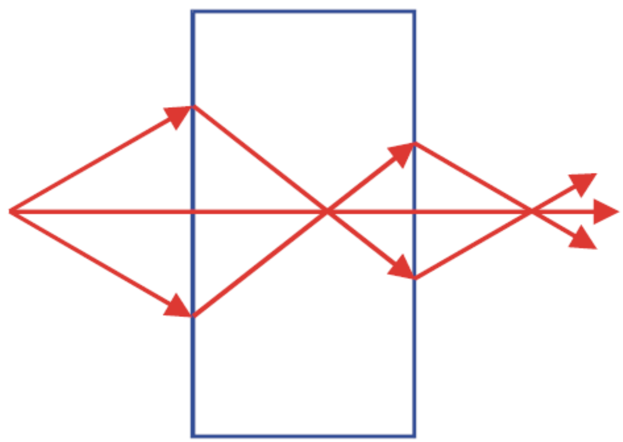


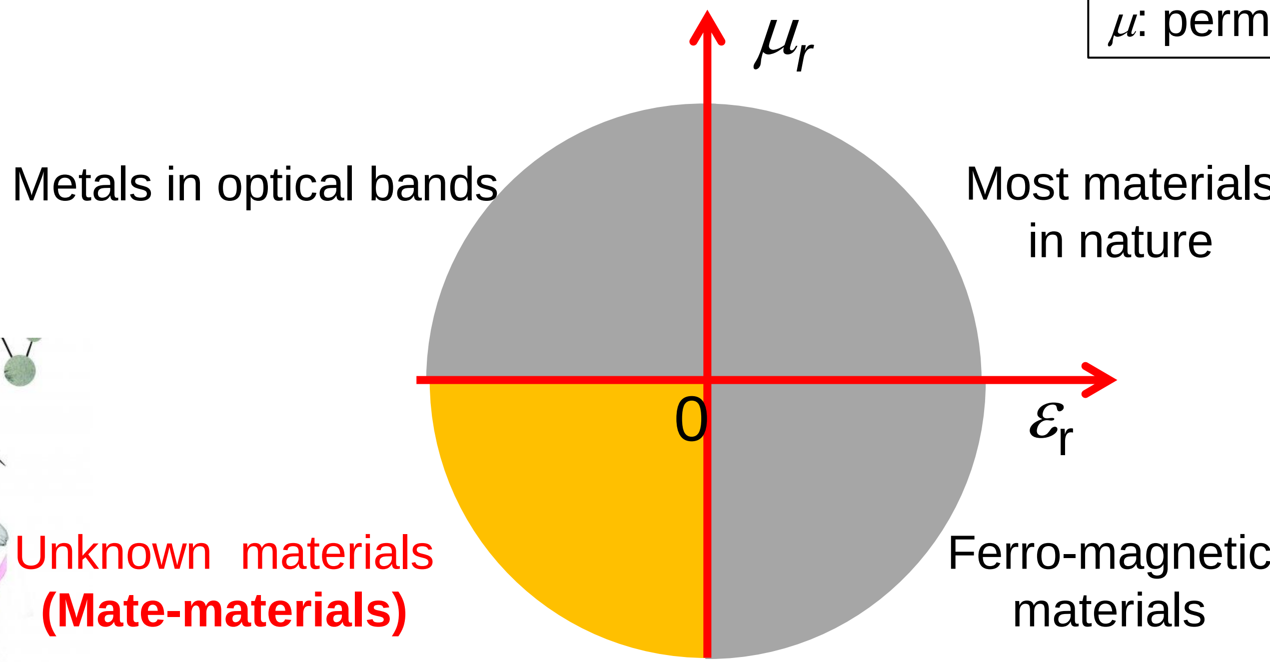
Figure 1. A negative refractive index medium bends light to a negative angle with the surface normal. Light formerly diverging from a point source is set in reverse and converges back to a point. Released from the medium the light reaches a focus for a second time.

"Negative Refraction Makes a Perfect Lens" by *JB Pendry, Phys. Rev. Lett.*, **85**, 3966 (2000).

Background Information: **Brief Historic Review**

Working in Quadrant III

ε: permittivity
μ: permeability



Notes: This idea proposed 40 years earlier by the Russian scientist **Victor Veselago**, who suggested that a material with a **negative refractive index**–never seen in nature–could produce an almost magical lens capable of creating images at a resolution finer than the wavelength of light being used. After that, the work related to metamaterials have been majorly focused double-negative materials.

Background Information: **Brief Historic Review**

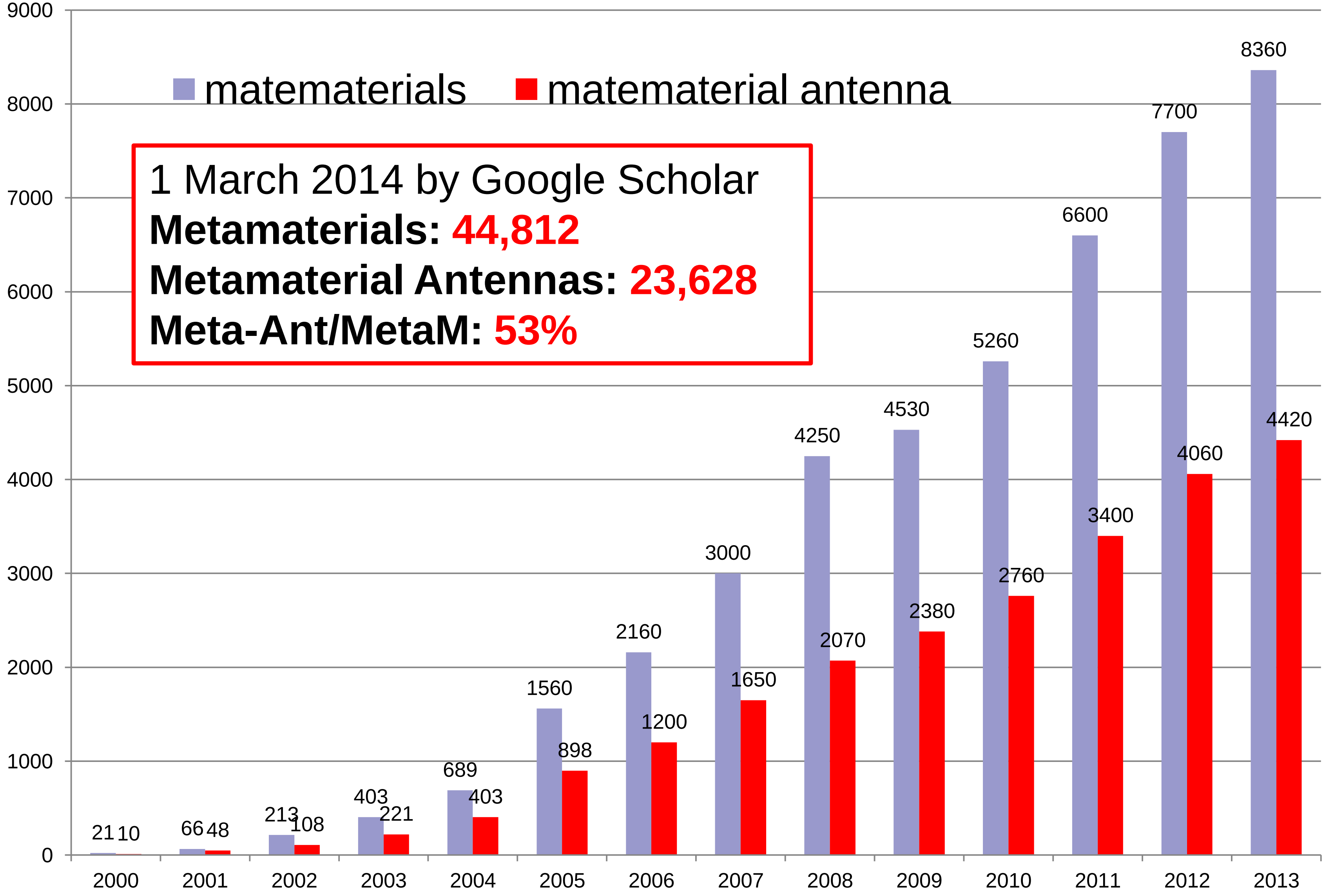
Updates of Publications since 2000

1 March 2014 by Google Scholar

Metamaterials: 44,812

Metamaterial Antennas: 23,628

Meta-Ant/MetaM: 53%



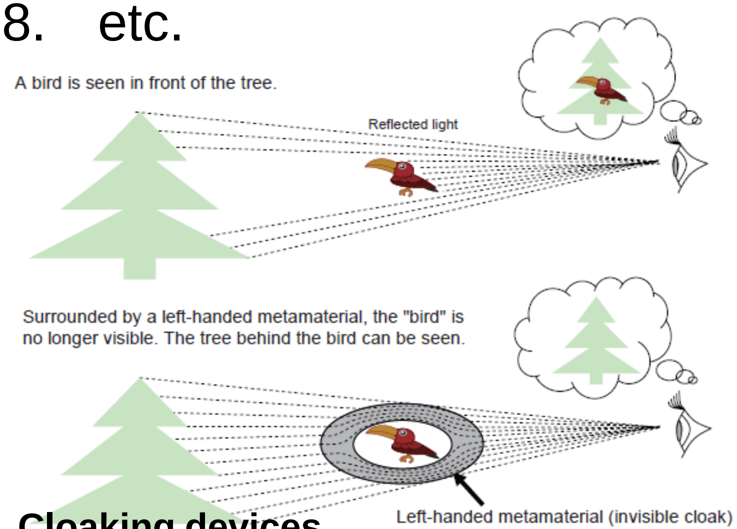
Background Information:

Potentials in EM Engineering

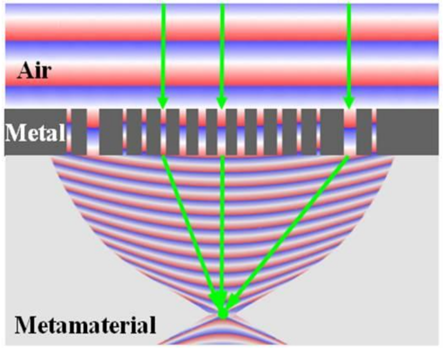
Frequency ranging from microwave, THz to optical:

1. Shielding,
2. Low-reflection materials (absorber),
3. Novel substrates/superstrate,
4. Antennas/sensors,
5. Electronic switches,
6. “Perfect lenses,”
7. Resonators, and
8. etc.

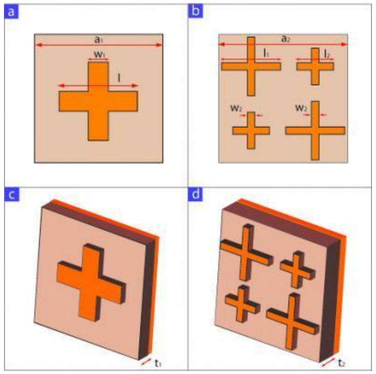
Antennas



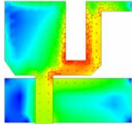
Cloaking devices



Superlens



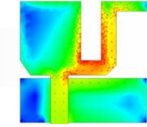
Absorber



Background Information:

Potentials in Antenna Engineering

- **To improve antenna design by:**
  - Lowering antenna profile (conformal/flexible)
  - Reducing antenna volume/weight/cost
  - Widening bandwidth (impedance/phase/gain)
  - Enhancing gain (efficiency/directivity)
  - Suppressing mutual coupling
  - Widening operating frequency tuning range
  - Achieving controllable beam (shaping/steering/lobe)



Background Information:

Potentials in Antenna Engineering: *Features*

meta	**Double Negative (DNG) Material→ ($\varepsilon<0$ & $\mu<0$)** **1960's & 2000's**	**Artificial Complex Impedance Surface →$Z_s = j\omega L/(1-\omega^2 LC)$** **1940's, 1970's, 1990's & 2000's**
features	▪Left-hand/negative index of refraction (NIR) ▪**Much less than a wavelength with backward propagation** ▪**Narrow bandwidth**	▪Electromagnetic bandgap (EBG) surface with pass/stop bands ▪Tunable impedance surface (TIS) with controllable reflection phase of 0-180º ▪**On order of one half wavelength or more** ▪**Narrow/moderate operating bandwidth**
applications	▪**DNI lens for high directivity** ▪**Zeroth order resonant antenna with reduced size** ▪**Series-fed array with improved beam-squint** ▪**Shell of antenna element**	▪**Patch antenna: directivity/efficiency** ▪**Dipole with reflector: directivity/ efficiency/ low profile** ▪**Waveguide/reflector/horn antenna: directivity** ▪**FSS**

Left/right handed scanning leaky wave antennas

Background Information:

Challenges in Antenna Engineering: *General*

- **Electrical:**
  - **Bandwidths:** performance of interest
  - **Gain:** directivity & efficiency
  - **Others:** polarization, isolation, beamwidth, etc.

- **Mechanical:**
  - **Size:** volume/conformal/low-profile
  - **Integration:** with other circuits
  - **Others:** robustness, lightweight, etc.

- **Commercialization (**mass production**):**
  - **Cost** (materials/process/fabrication & installation)

Background Information:

Challenges in Antenna Engineering: *Analysis*

Antennas	Metamaterials
Bandwidths: impedance/gain	Difficult but Possible
Gain: directivity & efficiency	Yes & Difficult
Size: volume/conformal/low-profile	Promising*
Integration: with other circuits	Promising
Cost: mass production (fabrication & materials)	Possible
Overall	**Promising ☺**

***overall** size against gain and bandwidth

Background Information:

State-of-the-arts in Antenna Engineering: *Example*

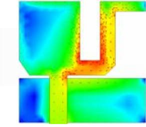
dipole/monopole/inverted-L/patch antenna:
high directivity & beam control

Used as superstrate (cover/lens/radome)

•artificial surfaces with controllable reflection phase
•artificial magnetic conductors (AMC)
•electromagnetic bandgap (EBG) surfaces

dipole/monopole/inverted-L antenna:
low profile & high directivity
patch antenna:
high directivity & efficiency & low coupling

Used as substrate (with ground plane)



Background Information:

State-of-the-arts in Antenna Engineering (incomplete)

- Suppression of inter-element mutual coupling: **MIMO**
- Low profile of antennas: **Cellular base-stations**
- Miniaturization of antennas (e.g. zero/negative-order resonator): **Portable devices**
- High gain for antennas with planar lens: **horns/patch**
- High gain of antennas with zero-index loading: **Vivadi@60GHz**
- Composite Right/Left-handed TL/LW antennas: **Beam-steering arrays**
- Zero-phase-shift-line loop antennas: **RFID**
- Controllable active metasurface arrays: **Satellite**

Notes: Many metamaterials-based technologies have been explored for antenna design. The incomplete list shows the technologies and their applications which have been claimed by the researchers in their publications and some startups.

Background Information:

State-of-the-arts in Antenna Engineering

Hype or Reality?

- Suppression of inter-element mutual coupling: **MIMO?**
- Low profile of antennas: **Cellular base-stations ? ?**
- Miniaturization of antennas (e.g. zero/negative-order resonator): **Portable devices ? ?**
- High gain for antennas with planar lens: **horns/patch**
- High gain of antennas with zero-index loading: **Vivadi@60GHz**
- Composite Right/Left-handed TL/LW antennas: **Beam-steering arrays ?**
- Zero-phase-shift-line loop antennas: **RFID**
- Controllable active metasurface arrays: **Satellite ? ?**

Notes: However, we have not had any chance to see metamaterials-based products in market so far although we have investigated on all antenna companies we can find out. We studied the metamaterials related patents and the description of the products which claimed that the designs are based on metamaterials.

Rethinking

Metamaterial Publications: 23,628

Metamaterial Antennas: ?

Notes: The observation raises a critical question how many ideas published in scientific and even engineering journals have been successfully translated into engineering designs such as antennas which really enhance the performance of designs in conventional ways or/and invent new methods for engineering design. In the other words, we need the translation from the physical concepts to engineering designs. How to bridge this gap?

Rethinking:

Antenna Engineering: Case Study

- Low profile of antennas: **Cellular Base-stations**

Key Parameters	**Requirements**
Operating Frequency, MHz	1710-2690 **(~45%)** (VSWR<1.6)
Size, wavelength@1710MHz	0.8x0.8**x0.10**
Gain, dBi with efficiency **>90%**	>7.0 at 1710 MHz; >11 at 2690 MHz
HP-Beamwidth	>**55±5** degree
Polarization	dual-linear , ±45 degree
Isolation of polarization	**>25 dB**
Front-to-Back ratio	**>22 dB**

Any solutions???

No way for any conventional methods.

Metamaterial-based solutions?

Rethinking

Metamaterial Publications

Metamaterial Antennas

Why and How?

? Inherent weakness of metamaterials (especially DNG) in terms of bandwidth, efficiency, size, etc.
(not due to DNG itself but existing approaches to realize DNG, using strong resonant structures)

? Too physical, enigmatic for engineers to understand/apply in design.
(good to describe physical phenomena using engineering languages such as RCL, S-parameters rather than index, even permittivity or permeability etc)

? A real magic
(ought to tell engineers real success stories of metamaterials in antenna design which have greatly enhanced performance, not potentials only.)

Rethinking

Definition of Metamaterials in Electromagnetics

“**meta**”: beyond

Metamaterials are **artificial** materials engineered to provide properties **not readily available in nature**.

These materials usually gain their properties from **structures rather than composition**, using the inclusion of small inhomogeneities to enact effective macroscopic behavior.

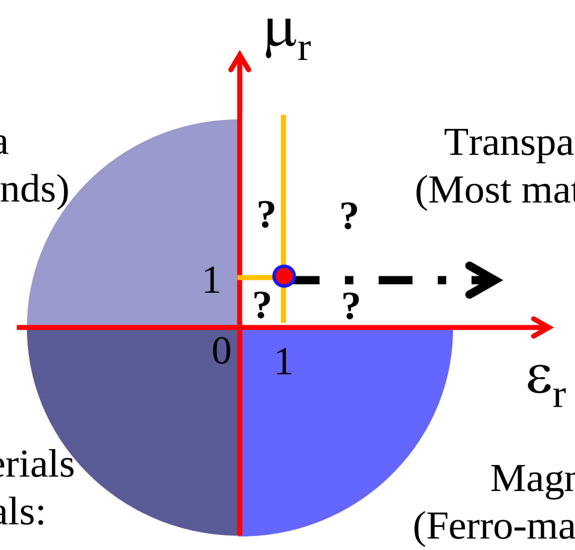
Notes: We may have to review the definition of Metamaterials and not limit us to DNG only.
From the definition mentioned above, the three key words have been highlighted in **red**. In the other words, all EM structures can be considered as metamaterials if they have all three key features.

Rethinking

Why ONLY Quadrant III?

Electrical Plasma
(Metals in optical bands)

Transparent Dielectric
(Most materials in nature)



Negative Index Materials
(Unknown materials:
double-negative or
backward-wave, or
left-handed materials)

Magnetic Plasma
(Ferro-magnetic materials)

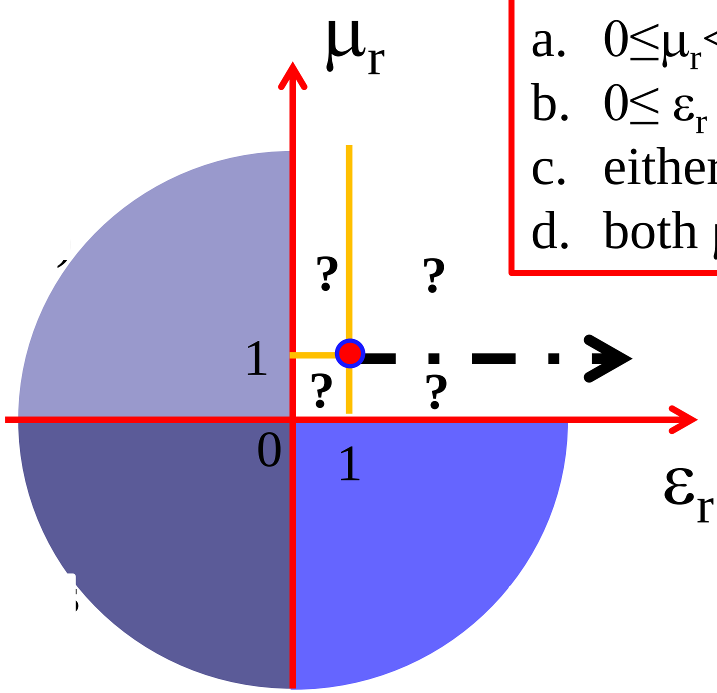
near-zero refractive index ($n = \sqrt{\varepsilon_r \mu_r}$)

Notes: Based on this thinking, we have a chance to explore the opportunities in other quadrants besides Quadrant III. For example, we can even look at Quadrant I for the structures which feature the magic properties that we have yet found in nature.

Z. N. Chen, "Metamaterials-based Antennas: *Translation from Physical Concepts to Engineering Technology*," Comments of FERMAT, February 2014 at www.e-fermat.org

Rethinking

Work on All Quadrants!



zones of interest in Q I

a. $0 \le \mu_r < 1$;
b. $0 \le \varepsilon_r < 1$;
c. either μ_r or $\varepsilon_r >> 1$;
d. both μ_r and $\varepsilon_r >> 1$.

Notes: Let us work on structures in all Quadrants not only Quadrant III, As well as other structures featuring unique EM properties such as anisotropicity, chirality and so on.

Z. N. Chen, "Metamaterials-based Antennas: *Translation from Physical Concepts to Engineering Technology*," Comments of FERMAT, February 2014 at www.e-fermat.org

Rethinking

Promising Translation from Physical Concepts to Engineering Technologies

Notes: The situation of metamaterials related R&D&C likes what is shown in the photo: the sun is rising to bring hopes to us although the beach and sea is still in dark due to the blockage of the mountains.

The photo was taken by Zhi Ning Chen in La Londe-les-Maures, Toulon, France in June 2013

Rethinking

Metamaterial-concept-based Antennas by Us

<table>
<tr><th>meta</th><th>Double Negative Material
(ε<0 & μ<0)</th><th>Artificial Complex Impedance Surface
→ $Z_s = j\omega L/(1-\omega^2 LC)$</th></tr>
<tr><td>feature</td><td>■Left-hand/Negative index of refraction-NIR
■Zero-phase-shift lines</td><td>■EBG surface with pass/stop bands
■Tunable impedance surface (TIS)</td></tr>
<tr><td rowspan="3">Applications</td><td>■Zero-phase-shift-line antennas
•Electrically large near-field RFID antennas
•Omni-directional CP antennas</td><td>■High permittivity dielectric
•Broadband low-profile dipole arrays
■High impedance surface
•Thin Fabry-Perot cavity antennas
•Broadband planar antenna</td></tr>
<tr><td colspan="2">■Zero-index antennas
•Gain-enhanced antipodal slot antennas
•High-gain patch antenna</td></tr>
<tr><td colspan="2">■Composite right/left-handed leaky wave antennas
•Consistent-gain array
•Broadband boresight radiation array</td></tr>
</table>

Rethinking :

Metamaterial-concept-based Antennas for Industry

- **Electrically Large:** Zero-phase-shift lines
  - UHF near-field RFID reader antennas
  - Omni-directional CP antennas

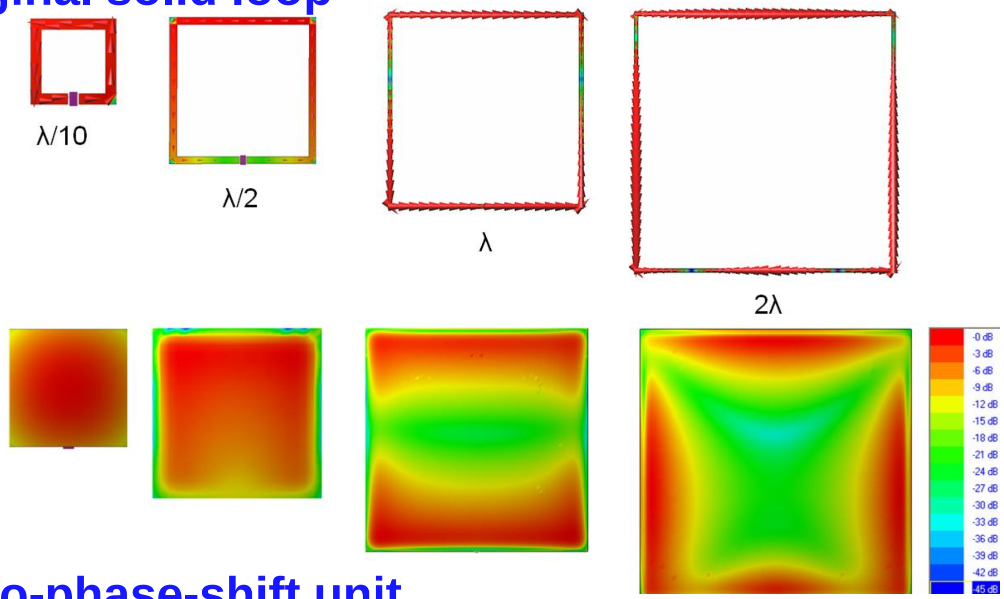
- **High-gain:** zero-index
  - Antipodal tapered slot antennas
  - Patch antennas

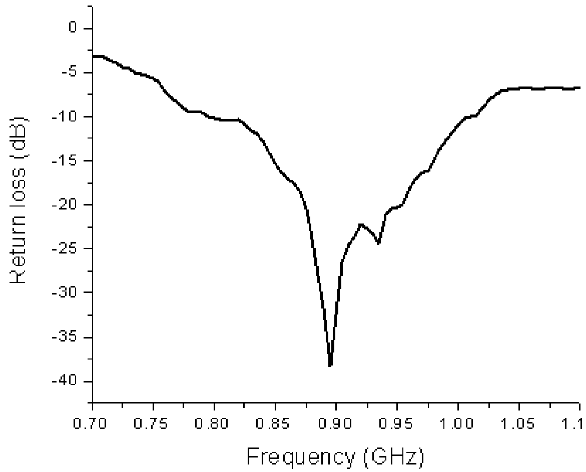
- **Low-profile:** High-permittivity/High Capacitive Surface/AMC
  - High-permittivity structure loaded broadband dipole array
  - High-capacity structure loaded broadband antenna
  - UHF near-field RFID AMC-loaded reader antennas

Zero-phase-shift-line-based Antennas: **Electrically Large**

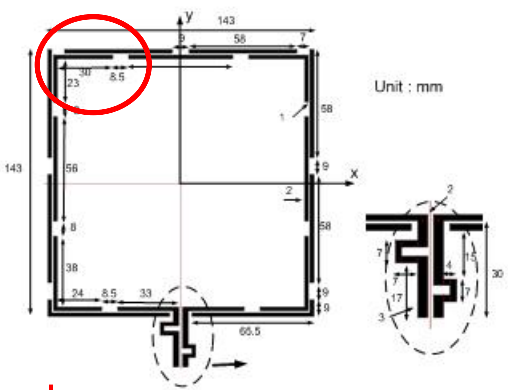
UHF Near-field RFID Reader Antennas

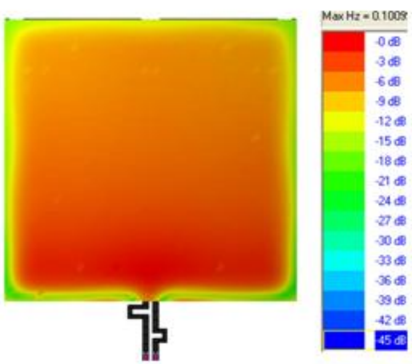
Original solid loop



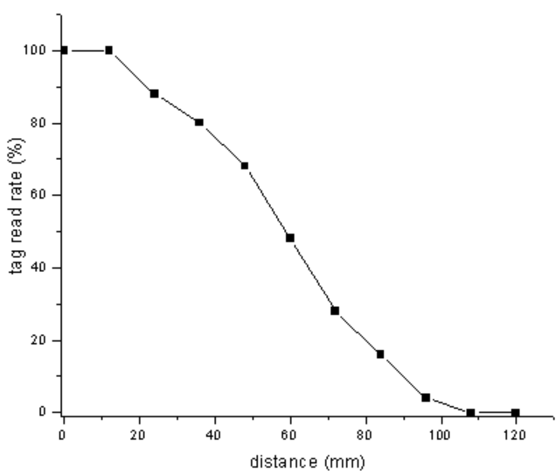


Zero-phase-shift unit





Tag read rate using the proposed reader antenna at different distance



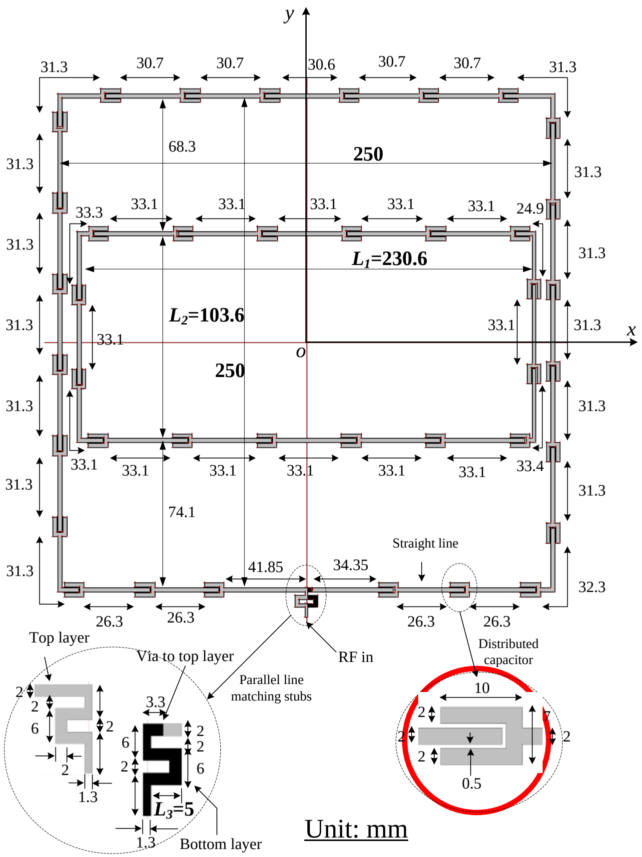
Patented

@915 MHz

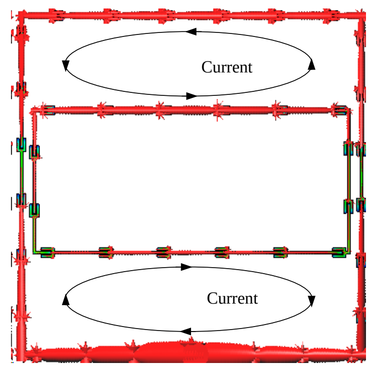
Qing, XM, Goh CK, and ZN Chen, A Broadband UHF Near-Field RFID Antenna, IEEE Trans. AP, vol.58, no.12, Dec 2010, pp.3829-3838

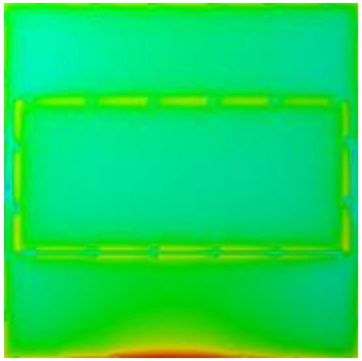
Zero-phase-shift-line-based Antennas: **Electrically Large**

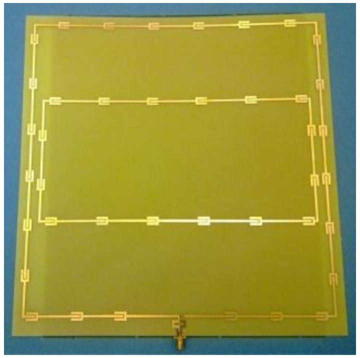
Near-field UHF RFID Reader Antennas

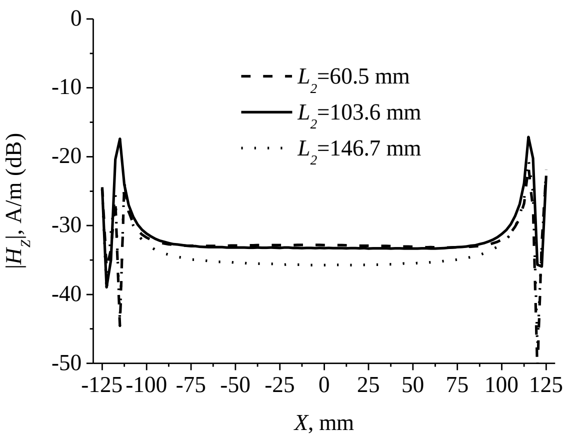


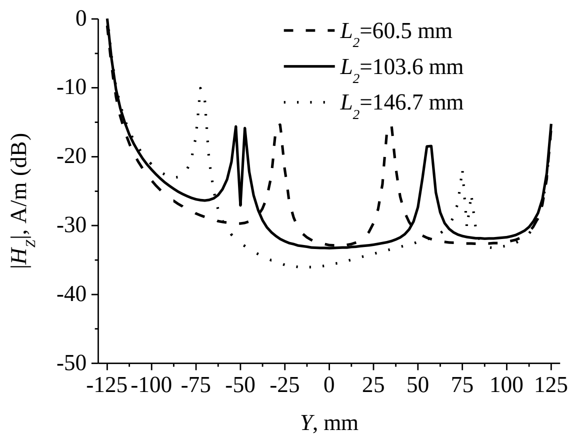
Zero-phase-shift unit









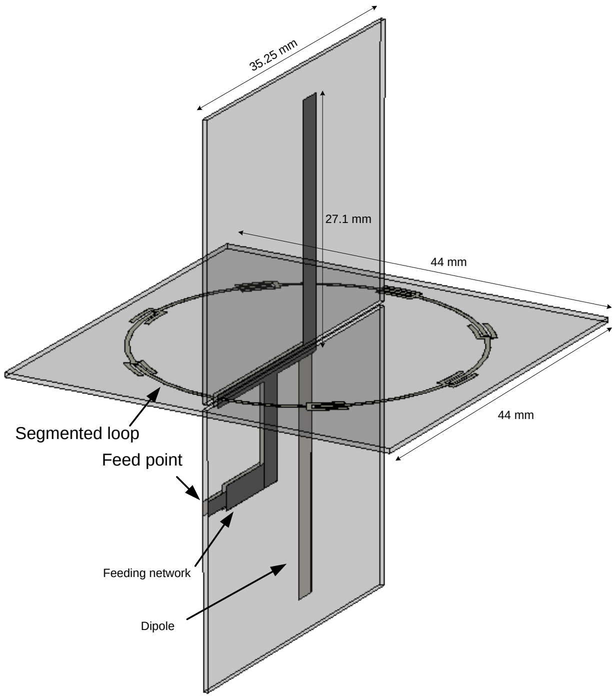


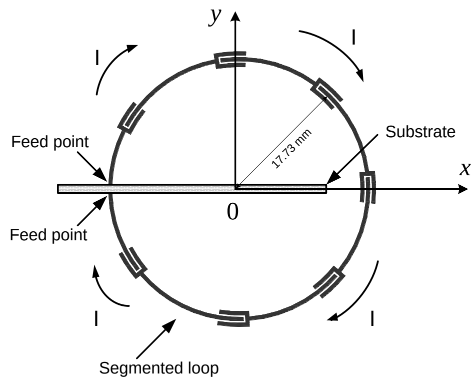
Maximum area up to 280×280mm (500x500 mm)

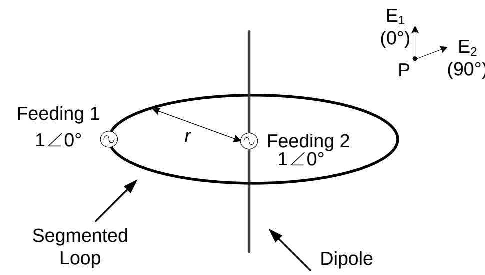
Patented

Zero-phase-shift-line-based Antennas: **Electrically Large**

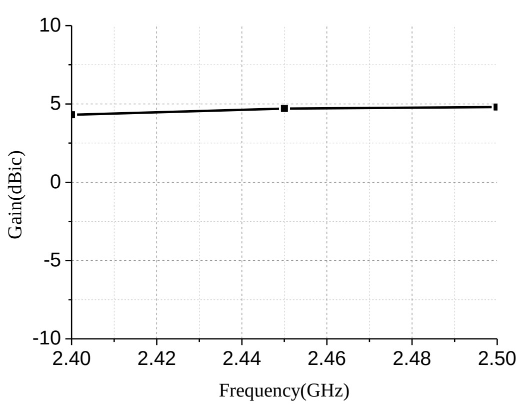
Omni-directional Circularly Polarized Antennas

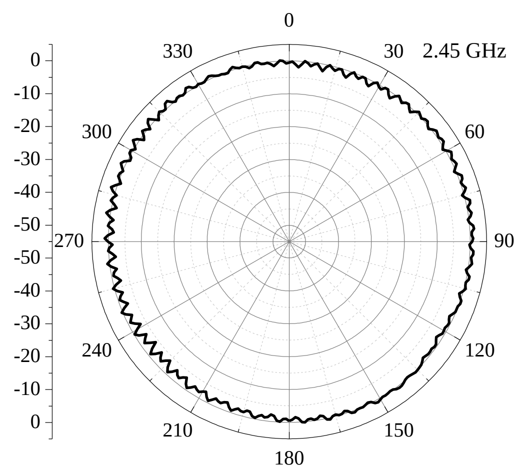


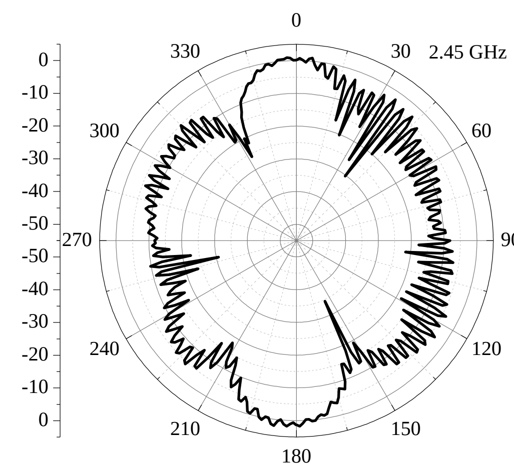




WLAN (2.4-2.5 GHz)







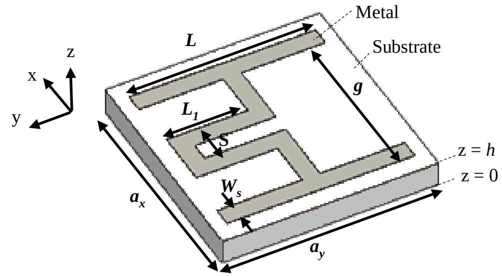
xy-plane

yz-plane

Patented

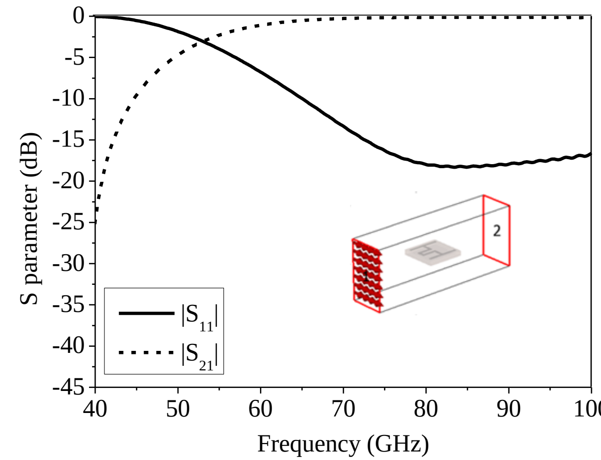
Zero-Index Antennas: **High Gain**

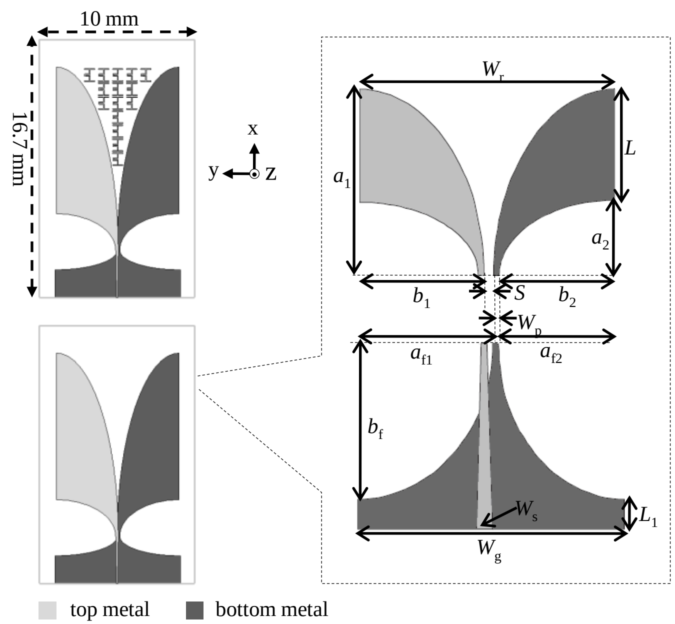
Antipodal Tapered Slot Antenna

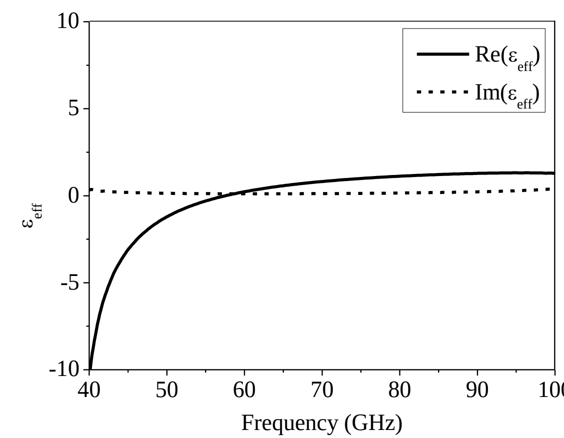


Proposed ZIM unit cell on a dielectric substrate.

@60-GHz





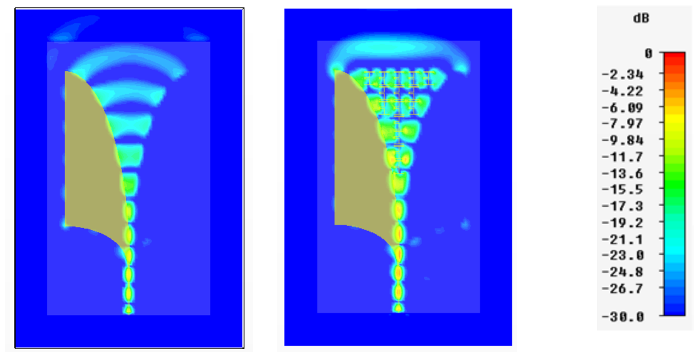


Characteristics of the ZIM unit cell: (a) S-parameter data and (b) retrieved effective permittivity.

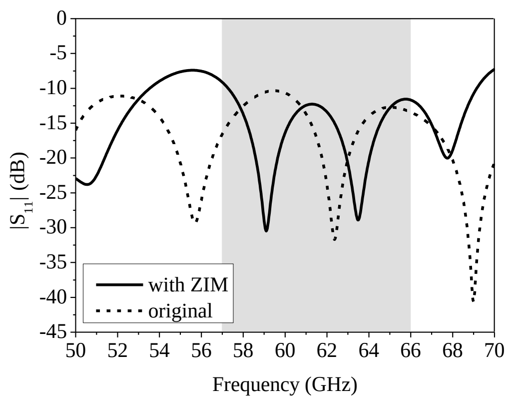
M. Sun, Z. N. Chen and X. Qing, “Gain Enhancement of 60-GHz Antipodal Tapered Slot Antenna Using Zero-Index Metamaterial”, IEEE Trans. AP, vol.61, no.4, Apr 2013, pp. 1741 - 1746

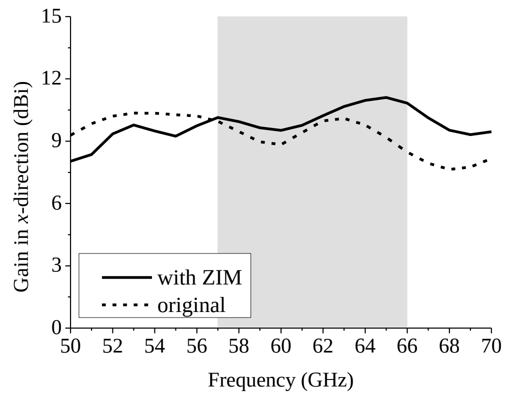
Rethinking: Case study

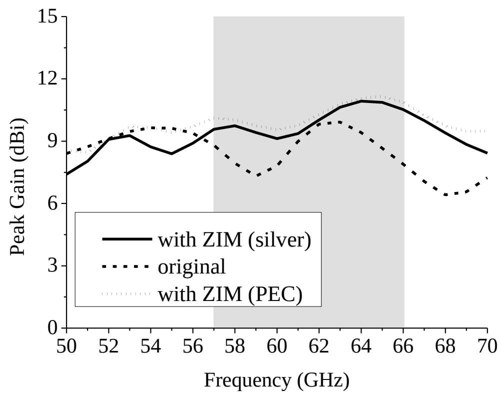
Gain-enhanced Antipodal Tapered Slot Antenna

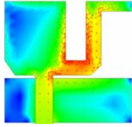


Field distribution of the antenna at 60 GHz (*xy* plane, *z* = *h*/2): (a) withoutZIM cells and (b) with ZIM cells.









Rethinking: **Case study**

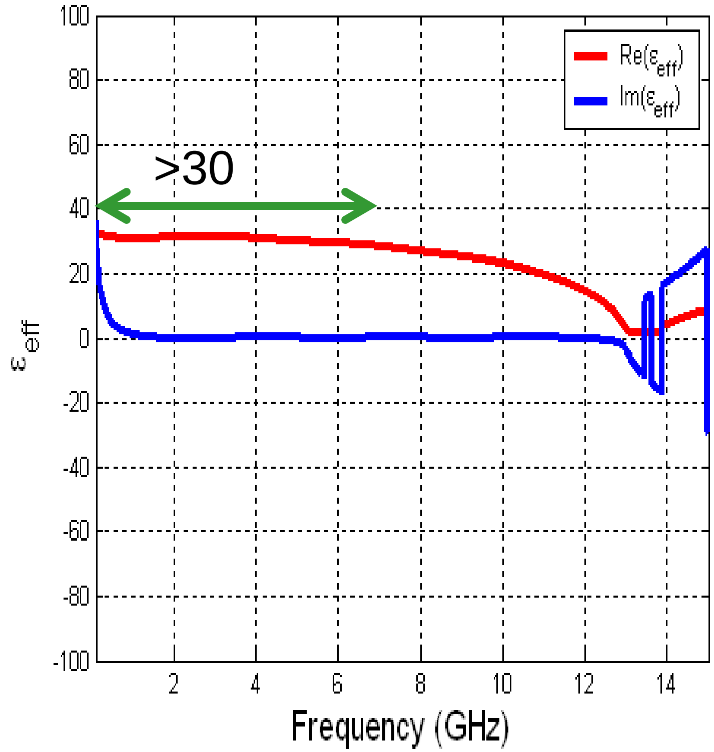
High & Anisotropic Permittivity Structure Loaded Low profile Broadband MIMO Antenna

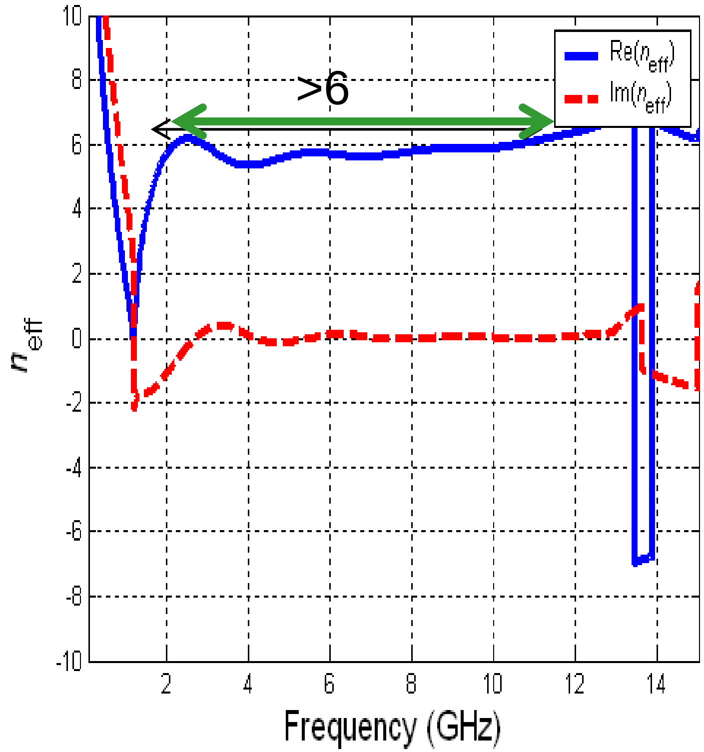
No.	Parameters	Specifications
1.	Operating Frequency	1.71-2.65GHz **(43%)** for VSWR<**1.5**
2.	Antenna size: mm	200x300x38 (1.14λx1.71λx0.22λ@1.71GHz)
3.	Gain	>12dBi
4.	Cross-Polarization	>25dB in all direction
5.	Sidelobe Level	>15dB
6.	Backlobe Level	-25dB
7	H-Plane Beamwidth	**20°~25° (10dB)**

Rethinking: Case study

High & Anisotropic Permittivity Structure Loaded Low profile Broadband MIMO Antenna

high permittivity >30 and high reflective index >6



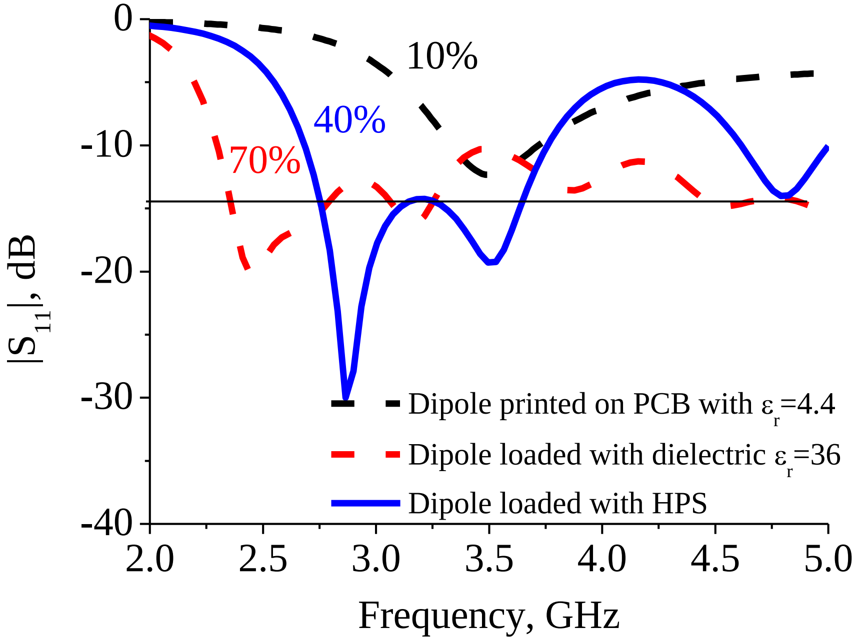


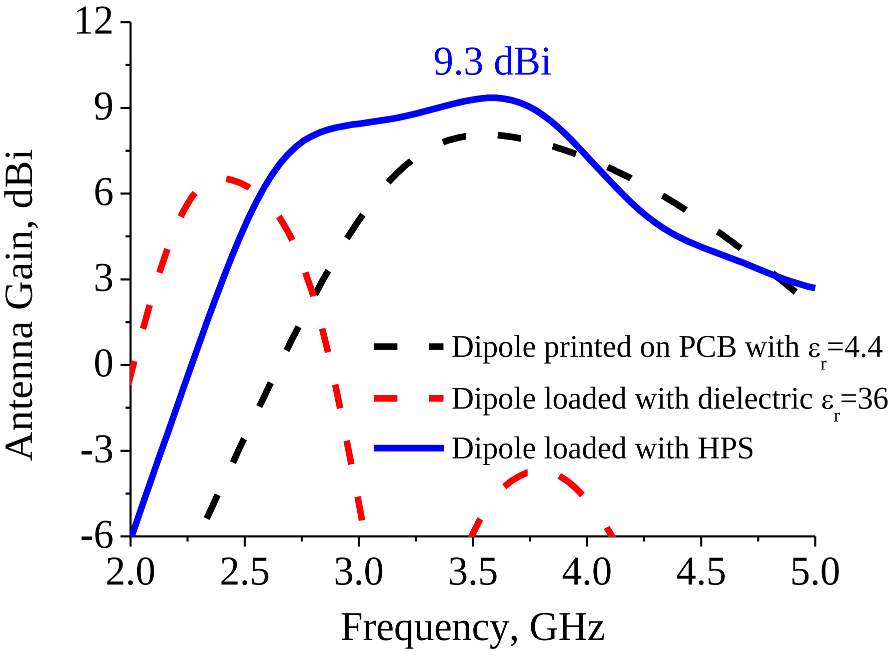
Permittivity is also anisotropic along x, y, z directions!

Rethinking: Case study

High & Anisotropic Permittivity Structure Loaded Low profile Broadband MIMO Antenna

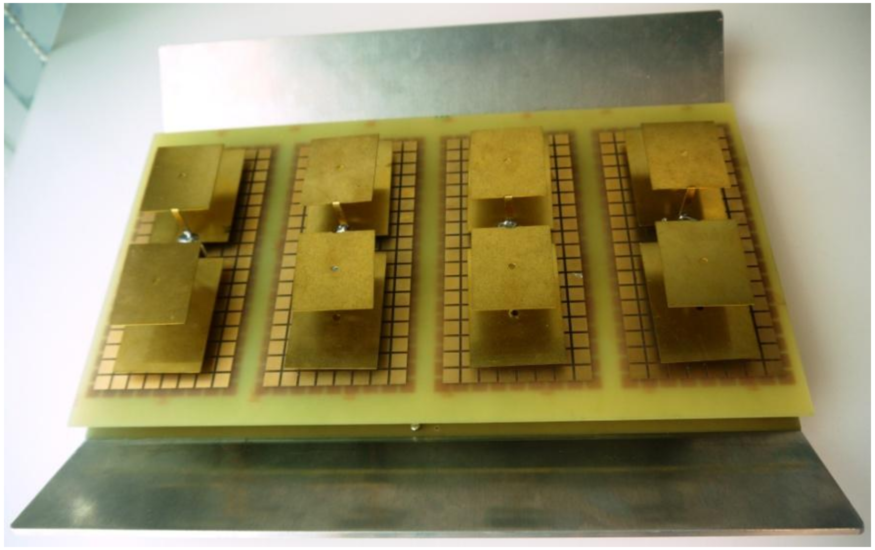
Comparisons of impedance matching and gain for single dipole antenna
(Air, high permittivity material, HAPS)





Rethinking: Case study

High & Anisotropic Permittivity Structure Loaded Low profile Broadband MIMO Antenna

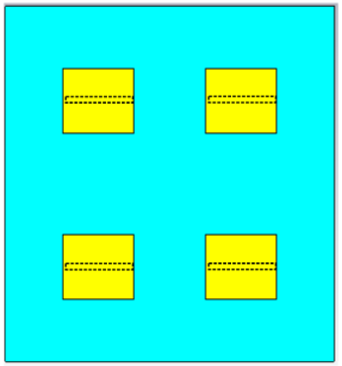


Patented

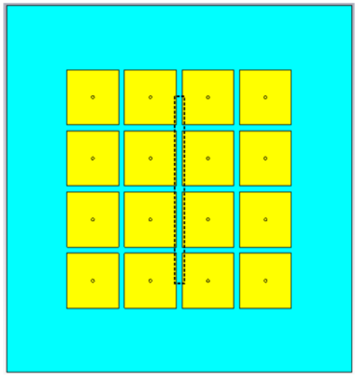
No.	Parameters	Specifications
1.	Operating Frequency	1.71-2.65GHz **(43%)** for VSWR<**1.5**
2.	Antenna size: mm	200x300x38 (1.14λx1.71λx0.22λ@1.71GHz)
3.	Gain	>12dBi
4.	Cross-Polarization	>25dB in all direction
5.	Sidelobe Level	>15dB
6.	Backlobe Level	-25dB
7	H-Plane Beamwidth	**20°~25° (10dB)**

Rethinking: Case Study

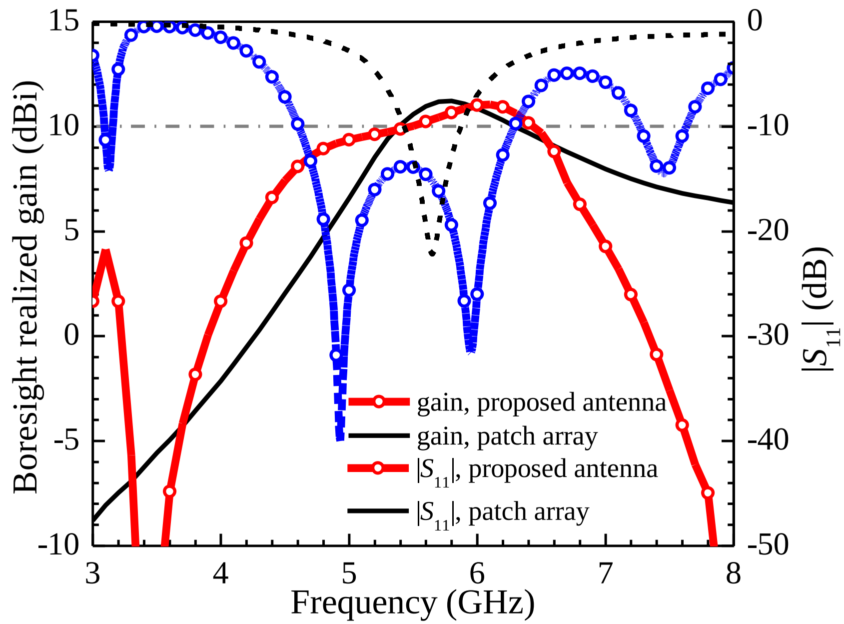
High-capacity-loaded Low-profile Broadband WLAN Antenna



Slot-fed patch array



Slot-fed wideband mushroom antenna



Boresight realized gain and $|S_{11}|$ of mushroom antenna and conventional patch array

Antenna	Impedance bandwidth ($\|S_{11}\| < -10$ dB)	Realized gain (dBi)	SLL (dB)	F/B (dB)
mushroom antenna	4.61-6.29 GHz, 30%	8.1 ~ 11.0	−6 ~ −11.2	7.5 ~ 14.6
Patch array	5.43-5.87 GHz, 8%	10.3 ~ 11.2	−12 ~ −12.3	12 ~ 12.3

W Liu, Z. N. Chen and X. Qing, "Metamaterial-Based Low-Profile Broadband Mushroom Antenna", IEEE Trans. AP, vol.62, no.3, Mar 2014, pp. 1165 - 1172

Rethinking: Case Study

AMC-loaded Low-profile Near-Field RFID Antennas

Impinj Antenna

67 mm

Pending for patent

Cavity-backed dual-loop antenna

55 mm

AMC-loaded cavity backed antenna

30 mm

My Comments

- **Fast development of wireless applications →strong increasing demand for high-performance antennas.**

Metamaterial, as a concept, has opened a new window for innovative antenna design!

- **Hot topics:**
  - **New methods to invent DNG structures for engineering**
  - **Translate the physical concepts to technology for applications**
    - Miniaturization / compact
    - Broadband / multiband
    - Diversity / co-existence
    - Tunable / switchable
    - Super gain
    - Low cost / cost effective

Debate Session@iWAT2014: **My Opinion**

1.metamaterial: a concept not technology but possibility**:**

- Everything possible (Q I,II& IV to Quadrant III)
- Thinking out-of-the-box
- Why limited to Quadrant III

2.metamaterial: possibility but aspirant

- Medicine to solve **all** "headache" (existing technical challenges)**??**
- Unique features for specific challenges

Debate Session@iWAT2014: **My Opinion**

3.metamaterial: opportunity-suggestion

- **Scientists**: exploring physical issues for crazy ideas
- **Engineers**: understand and translate the ideas for tech

4. My views

- **Scientists**: opportunity when things unclear/unknown
- **Engineers**: opportunity when things clear/well-known

All questions, comments, and suggestions are welcome!

Merci!

Thank you!

谢谢！

Terima kasih !

Nandri!

ありがとうございます

Danke!

감사합니다

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